EVIDENCE FOR TURBULENT CONCENTRATION IN PARTICLE-LADEN MIDPLANE LAYERS OF PLANET-FORMING DISKS: PRELIMINARY FINDINGS. O.M. Umurhan[1,2,3], P.R. Estrada[2], D. Sengupta[4], [1]SETI Institute, Mountain View, CA 94035 (oumurhan@seti.org), [2]NASA-Ames Research Center (Paul.R.Estrad@nasa.gov), [3]Cornell University, [4]New Mexico State University (debanjan@nmsu.edu).

Introduction: The formation of the first planetesimals during the first million years of the solar nebula remains a vexing problem. The Streaming Instability (SI) is the leading candidate mechanism that offers a route to form 100 km objects from mm-sized grains, but it appears to not be strongly active based on recent findings [1]. The idea of turbulent concentration offers a possible alternate route to forming these bodies. Is there evidence for this process in bonafide 3D disk models of particle-gas dynamics?

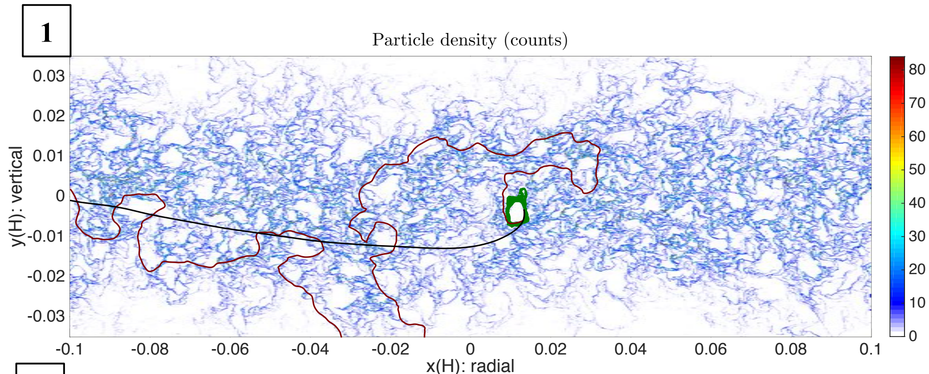
Precepts of Turbulent Concentration (TC): Laboratory and numerical experiments demonstrate that aerosols in isotropic incompressible turbulence are centrifugally expelled from regions of low-strainrate/high-vorticity and collect/flow along regions of high strain-rate/low-vorticity [2]. On the lifetime of a turbulent eddy with rotation time $1/\omega$, particles that are most efficiently moved are those whose drag stopping times, t_s, are such that $t_s\omega \approx 0.3$ [3]. The strain-rate/vorticity of the flow is measured by the second invariant of the deformation tensor, Π, but we consider instead the magnitude of the strainrate tensor, defined as $S^2=S_{ij}S_{ji}$, where $S_{ij} = (\partial u_i/\partial x_j - \partial u_i/\partial x_j)/2$, to be a suitable proxy for Π.

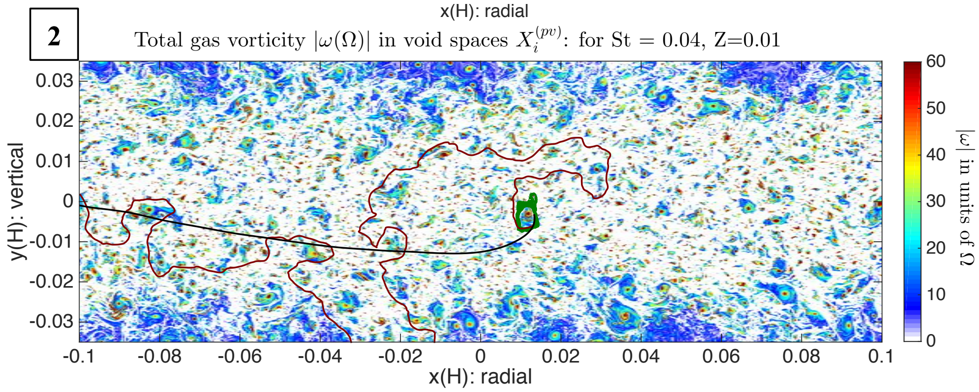
Numerical Experiment: Using the PENCIL code numerical framework, we consider the fate of particles in a 3D axisymmetric shearing box setting, with global rotation rate Ω, experiencing its own self-generated turbulence with no self-gravity [4]. We consider a monodisperse particle size distribution with Stokes number St = $t_s\Omega$ = 0.04, with local metallicity Z=0.01, and an imposed non-dimensionalized radial pressure gradient parameter Π=0.05. The box size is $L_x = L_z = 0.2H$, where H is the local gas pressure scale height. Numerical resolution of the gas grid $N_x = N_z = N$= 2048 and the number of superparticles is N^2, which translates to the density of 1 superparticle $\rho_{par} = 0.125\rho_{gas}$. Examining [5] shows that for the parameter set [St, Z, Π] adopted here, Roche-density exceeding particle overdensities (attributed to the formation of high density filaments) should become manifest at a time somewhere between $t\Omega$=257 and $t\Omega$=603. In order to seek evidence for TC in the particle-gas field generated by the turbulence of our simulation, we examine our simulation output at a time well before such extreme overdensities should start appearing, i.e., at $t\Omega$=80.

Preliminary Results: Fig. 1 displays particle distribution once the midplane shear turbulent state described in [4] takes root. Particles are concentrated in filaments with prominent void spaces appearing. Fig. 2 displays the total (scalar) gas vorticity (ω) within these void spaces (vorticity in filaments are whited out), showing that flow is strongly organized within. We examine the trajectory of test particles by taking the gas velocity field as given and forward evolving particles using an independent Runge-Kutta fourth order method. A particle is placed in the center of a void and allowed to evolve. The centrifugal flinging predicted by TC is clearly evident for the test particle with St = 0.001, 0.04. The St = 1 particle is unaffected by the void and rapidly drains star-ward. Once the small St particles leave the void region they travel along star-ward meandering trajectories steering clear of vortex containing void regions. Fig. 3 also shows a close-up region of the gas vorticity and particle distribution. Superimposed upon them are the velocity vectors of the particles in filaments (right panel) and of gas flow inside voids (middle panel). The particle velocity vectors clearly respect void locations, moving around them accordingly. The right panel of Fig. 3 shows the strainrate distribution of the corresponding region and visually indicates that locations of high particle accumulation correlates with high strainrate in comparison with void spaces. Fig. 4 shows normalization distributions of the so-called eddy Stokes number, defined as $St_{eddy} = St\cdot(\omega/\Omega)$, within all void spaces in the particle layer. The distribution peaks at St_{eddy} (peak) ≈ 0.3, as predicted to be evidence of TC [3]. The right panel of Fig. 4 shows the distribution of S distinguished by void spaces and filaments. Filaments exhibit larger values of S compared to voids, evidently consistent with predictions [2].

Tentative Conclusions: *These findings suggest that TC is always present in midplane layers of planet forming disks and likely helps the SI to achieve gravitationally bound overdensities – all of which warranting further investigation.*

References: [1] Estrada & Umurhan (2023) this meeting. [2] Squires & Eaton (1991), *Phys Fl.* 3, 1169. [3] Hartlep & Cuzzi (2017), *PhysRev E* 033115. [4] Sengupta & Umurhan (2022), *arXiv*, 2209.11205. [5] Li & Youdin (2021), *ApJ*, 919, 107.





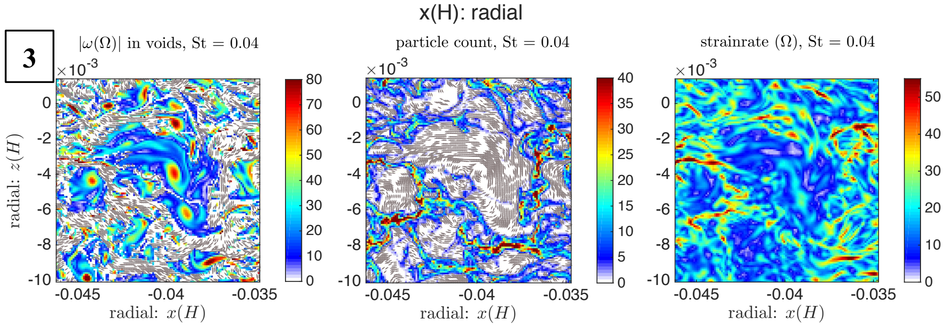


Figure 1. Particle count distribution. Particles are collected into filamentary structures. **Figure 2**. Total gas vorticity inside void spaces shown. Figures 1and 2 display trajectory of test particles with St = 0.001 (green), St = 0.04 (red), and St = 1 (black). **Figure 3**. Close up region showing structured total gas vorticity ω in void spaces with particle velocity vectors in filamentary spaces displayed (right), particle distribution with gas flow velocity vectors in void spaces (middle), and S distribution. S is generally higher in regions containing particles and lower in void regions. **Figure 4** (below) shows normalized global distribution of eddy St in void spaces (left) and distribution of S as per either void or filament locations (right).